Search for Neutral B Meson Decays to Two Charged Leptons

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Abstract

The decays B_d^0, $B_s^0 \to e^+e^-$, $\mu^+\mu^-$, $e^\pm\mu^\mp$ are searched for in 3.5 million hadronic Z events, which constitute the full LEP I data sample collected by the L3 detector. No signals are observed, therefore upper limits at the 90%(95%) confidence levels are set on the following branching fractions:

$$\begin{array}{ll} \mathrm{Br}(B_d^0 \to e^+e^-) < 1.4(1.8) \times 10^{-5}; & \mathrm{Br}(B_s^0 \to e^+e^-) < 5.4(7.0) \times 10^{-5}; \\ \mathrm{Br}(B_d^0 \to \mu^+\mu^-) < 1.0(1.4) \times 10^{-5}; & \mathrm{Br}(B_s^0 \to \mu^+\mu^-) < 3.8(5.1) \times 10^{-5}; \\ \mathrm{Br}(B_d^0 \to e^\pm\mu^\mp) < 1.6(2.0) \times 10^{-5}; & \mathrm{Br}(B_s^0 \to e^\pm\mu^\mp) < 4.1(5.3) \times 10^{-5}. \end{array}$$

The results for $B_s^0 \to e^+e^-$ and $B_s^0 \to e^\pm\mu^\mp$ are the first limits set on these decay modes.

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Introduction

Measurements of rare B hadron decay rates provide clean tests of the Standard Model and are in general sensitive to new physics. $B^0 \to \ell^+\ell^-$ decays [1)] are particularly clean both theoretically and experimentally. The flavour-changing neutral current decays, $B^0 \to e^+e^-$ and $B^0 \to \mu^+\mu^-$, are forbidden at tree level. They occur in the Standard Model due to higher-order processes with branching fractions $< \mathcal{O}(10^{-9})$ [1], which is beyond the sensitivity of LEP, and are sensitive to the Cabibbo-Kobayashi-Maskawa matrix elements, the top quark mass, and the B meson decay constants. $B^0 \to e^\pm\mu^\mp$ decays violate lepton number conservation and are forbidden in the Standard Model.

Observation of $B^0 \to \ell^+\ell^-$ decays at LEP would be a clear indication for physics beyond the Standard Model. For example, two Higgs doublet models predict significant enhancements to the $B^0 \to \ell^+\ell^-$ decay rates [2–5].

This analysis is performed on data recorded during 1991-1995 running at the Z, corresponding to a sample of approximately 3.5 million hadronic Z decays. The mixed sample of B hadrons produced in Z decays provides an opportunity to study B_s^0 meson decays which are not accessible at the center-of-mass energy of the $\Upsilon(4S)$.

The L3 Detector

The L3 detector is described in detail elsewhere [6, 7]. The central tracking chamber is a Time Expansion Chamber (TEC) consisting of two coaxial cylindrical drift chambers with 12 inner and 24 outer sectors. The Z-chamber surrounding the TEC consists of two coaxial proportional chambers with cathode strip readout. The electromagnetic calorimeter is composed of bismuth germanate (BGO) crystals. Hadronic energy depositions are measured by a uranium-proportional wire chamber sampling calorimeter surrounding the BGO. Scintillator time-of-flight counters are located between the electromagnetic and hadronic calorimeters. The muon spectrometer, located outside the hadron calorimeter, consists of three layers of drift chambers measuring the muon trajectory in both the bending and the non-bending planes. All subdetectors are installed inside a solenoidal magnet which provides a uniform field of 0.5 T.

The invariant mass resolution of pairs of electrons measured in the BGO calorimeter is approximately 70 MeV for the typical kinematics of $B^0 \to e^+e^-$ decays. Similarly, the di-muon mass resolution is 180 MeV and the $e^\pm\mu^\mp$ mass resolution is 140 MeV.

Simulation of $B^0 \to \ell^+\ell^-$ decays and backgrounds

The JETSET Monte-Carlo program [8, 9] is used to simulate hadronic Z decays. To model b quark fragmentation the Peterson function [10] is used as a function of $x_E = 2E_{hadron}/\sqrt{s}$, with a mean value of $\langle x_E \rangle = 0.703$. The masses of the B_d^0 and B_s^0 mesons are assumed to be 5279 MeV and 5373 MeV respectively, which are consistent with the most recent world average values [11]. The events produced by JETSET are passed through the GEANT-based L3 detector simulation program [12] which allows for the effects of energy loss, multiple scattering, decays and interactions in the detector material, as well as time-dependent detector effects. These events are then reconstructed using the same algorithms as for the data.

[1)] Throughout this paper we use B^0 to denote either B_d^0 or B_s^0, and $\ell^+\ell^-$ to denote e^+e^- or $\mu^+\mu^-$ or $e^\pm\mu^\mp$. The latter case is a sum of $e^+\mu^-$ and $e^-\mu^+$.

To study the sensitivity of the L3 detector to events containing $B^0 \to \ell^+\ell^-$ decays, we first simulate $e^+e^- \to b\bar{b}$ events. $B^0_{d,s}$ mesons are forced to decay via the chain $B^0_{d,s} \to \ell^+\ell^-$ ($\ell = e, \mu$). If, however, there is more than one $B^0_{d,s}$ meson in the event, only one is required to decay in this way. For the background studies a sample of hadronic events is used which does not include the $B^0 \to \ell^+\ell^-$ decay modes.

Event Selection

Hadronic events are selected by making use of their characteristic energy distributions and high multiplicity [13]. A total of 3 453 780 events from the 1991-1995 data samples are selected.

Candidate electrons are selected in the barrel and endcap BGO calorimeters within $|\cos\theta| < 0.97$, where θ is the polar angle. An electron is characterized by an isolated energy cluster in the BGO with a shower shape consistent with that of electromagnetic particles. To reject photons, the cluster is required to match with a charged track to within 5 mrad in the plane transverse to the beam direction. Electron candidates are required to have an energy of more than 2 GeV.

Muon candidate tracks in the muon spectrometer are required to be within $|\cos\theta| < 0.8$ and to have hits in at least two of the three $r\phi$ layers and at least one of the two z layers. Backgrounds from punchthrough hadrons, decays in flight, and cosmic rays are suppressed by requiring the muon chamber track to point towards the primary vertex. Residual contamination due to cosmic rays which coincide with a genuine hadronic event is reduced to a negligible level by scintillator timing cuts. Muon candidates are required to have a momentum of more than 2 GeV.

Due to the hard fragmentation of the b quark, the energy carried by the two leptons from a B^0 decay is large. Pairs of oppositely charged candidate leptons are therefore required to have a combined energy of more than 20 GeV. The opening angle of the candidate lepton pair is required to be less than 90°, to ensure that both lepton candidates originated from the decay chain of the same primary quark. After these cuts the background consists predominantly of fake leptons with a small irreducible contribution from the decay chain $b \to c\ell^-\bar{\nu}$; $c \to s\ell^+\nu$.

After applying these selection criteria the efficiencies, $\epsilon(B^0 \to \ell^+\ell^-)$, are determined from Monte Carlo studies to be $\epsilon(B^0 \to e^+e^-) = (39.0 \pm 5.2)\%$, $\epsilon(B^0 \to \mu^+\mu^-) = (39.2 \pm 4.8)\%$, and $\epsilon(B^0 \to e^\pm\mu^\mp) = (39.4 \pm 4.1)\%$, where the errors are dominated by systematic effects. The systematic errors are estimated by comparing the data and Monte Carlo distributions of the selection variables with various less stringent values for the cuts applied. A small contribution is also included from the uncertainty in the b quark fragmentation function.

Determination of Branching fractions

Figure 1 shows the expected invariant mass distributions after application of the selection procedure described above, for a) $B^0 \to e^+e^-$, b) $B^0 \to \mu^+\mu^-$, and c) $B^0 \to e^\pm\mu^\mp$. Each is normalised to the integrated luminosity of the data and corresponds to a nominally assumed branching fraction of $Br(B^0 \to \ell^+\ell^-) = 10^{-5}$ for each process.

Figure 1 also shows the mass spectra obtained from the data (solid line) for d) e^+e^-, e) $\mu^+\mu^-$, and f) $e^\pm\mu^\mp$. The dashed line represents the background contribution which is estimated from the Monte-Carlo sample of hadronic Z decays for which the same selection used for the data is applied. No signal is seen for $B^0_{d,s} \to e^+e^-$, $B^0_{d,s} \to \mu^+\mu^-$, or $B^0_{d,s} \to e^\pm\mu^\mp$ decays.

Upper limits on the branching fractions for these processes are obtained from binned maximum-likelihood fits to the $\ell^+\ell^-$ invariant mass distributions. For each di-lepton sample, the signal comprises two components, corresponding to B^0_d and B^0_s decays. The likelihood function is given by:

$$\mathcal{L}(\mu_d, \mu_s) = \prod_{i=1}^{n_{bins}} \frac{e^{-(\mu_{b,i}+\mu_{d,i}+\mu_{s,i})}(\mu_{d,i} + \mu_{s,i} + \mu_{b,i})^{N_i}}{N_i!}$$

where N_i is the number of observed data events in mass bin i, and $\mu_{d,i}$, $\mu_{s,i}$, and $\mu_{b,i}$ denote the expected numbers of events for B^0_d, B^0_s, and background respectively.

The mass-dependences of the B^0_d and B^0_s signal components, $\mu_{d,i}$ and $\mu_{s,i}$ respectively, are taken from figures 1a), 1b), and 1c). The total signal components, μ_q ($q = d, s$), are given by:

$$\mu_q = \sum_{i=1}^{n_{bins}} \mu_{q,i} = \mathrm{Br}(B^0_q \to \ell^+\ell^-) \times N_h \times 2 \times R_{b\bar{b}} \times f_q \times \epsilon(B^0 \to \ell^+\ell^-)$$

where $N_h = 3\,453\,780$ is the total number of hadronic Z decays and $R_{b\bar{b}} \equiv \Gamma_{b\bar{b}}/\Gamma_{had} = 0.222 \pm 0.0076$ is taken from the L3 measurement [13]. The fractions $f_d = (37.8 \pm 2.2)\%$ and $f_s = (11.2^{+1.8}_{-1.9})\%$ [14] are the probabilities that a b quark is dressed in the fragmentation to become a B^0_d or B^0_s meson respectively.

The background component, $\mu_{b,i}$, is determined using the Monte Carlo sample of $e^+e^- \to$ hadrons events. The expected numbers of background events within $\pm 3\sigma$ are 0.8, 2.6, and 2.4 events respectively for the e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ final states. The systematic errors on the background of between 10% and 13% include detector effects, which are estimated by relaxing the selection cuts and comparing the data and Monte Carlo distributions of the selection variables. This procedure accounts for systematic detector effects, uncertainties on the b quark fragmentation function, the heavy quark semi-leptonic branching fractions, and $R_{b\bar{b}}$. The statistical error on the background is parametrised by a Poisson distribution.

The likelihood is evaluated as a function of the branching fractions $\mathrm{Br}(B^0_d \to \ell^+\ell^-)$ and $\mathrm{Br}(B^0_s \to \ell^+\ell^-)$, taking into account the errors on $R_{b\bar{b}}$, f_d, f_s, the efficiencies, and the background parameterization. By varying $\mathrm{Br}(B^0_d \to \ell^+\ell^-)$ and $\mathrm{Br}(B^0_s \to \ell^+\ell^-)$ simultaneously we obtain the two-dimensional likelihood distribution. The one-dimensional likelihood distributions for the B^0_d (B^0_s) branching fractions are obtained by integrating the likelihood over all the values of the B^0_s (B^0_d) branching fractions. The 90%(95%) confidence level limits are

$$\begin{array}{ll}
\mathrm{Br}(B^0_d \to e^+e^-) < 1.4(1.8) \times 10^{-5}; & \mathrm{Br}(B^0_s \to e^+e^-) < 5.4(7.0) \times 10^{-5}; \\
\mathrm{Br}(B^0_d \to \mu^+\mu^-) < 1.0(1.4) \times 10^{-5}; & \mathrm{Br}(B^0_s \to \mu^+\mu^-) < 3.8(5.1) \times 10^{-5}; \\
\mathrm{Br}(B^0_d \to e^\pm\mu^\mp) < 1.6(2.0) \times 10^{-5}; & \mathrm{Br}(B^0_s \to e^\pm\mu^\mp) < 4.1(5.3) \times 10^{-5}.
\end{array}$$

The results for $B^0_s \to e^+e^-$ and $B^0_s \to e^\pm\mu^\mp$ are the first limits set on these decay modes. The results for $B^0_d \to e^+e^-$, $B^0_d \to \mu^+\mu^-$, $B^0_d \to e^\pm\mu^\mp$, and $B^0_s \to \mu^+\mu^-$ are consistent with the slightly more stringent limits from CLEO [15] and CDF [16].

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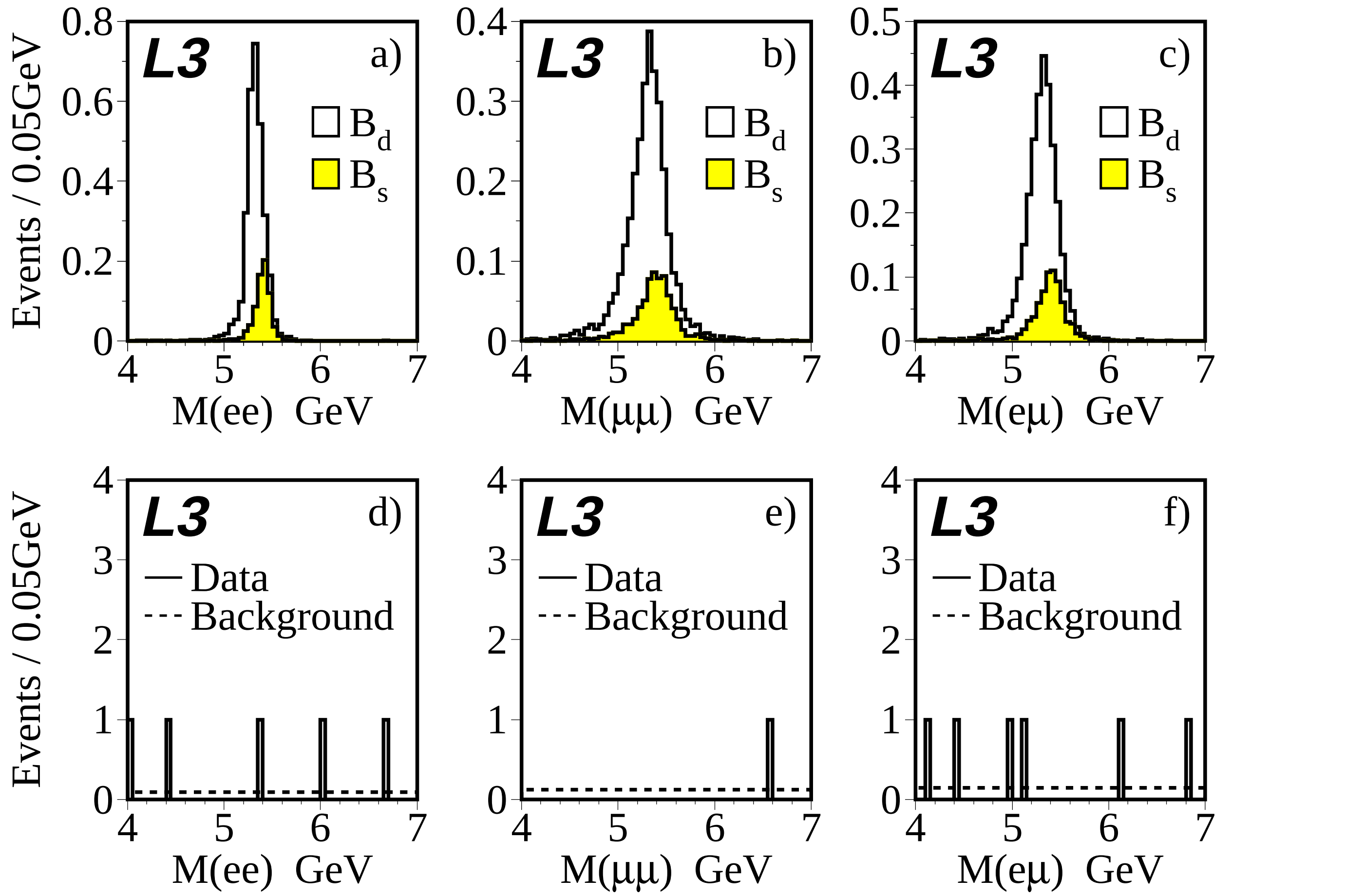

Figure 1. Predictions for the dilepton invariant mass distributions for a) $B^0 \to e^+e^-$, b) $B^0 \to \mu^+\mu^-$, and c) $B^0 \to e^\pm\mu^\mp$ decays, assuming the integrated luminosity and efficiencies of this analysis and a nominal branching fraction of $Br(B^0 \to \ell^+\ell^-) = 10^{-5}$ for each process.

Mass spectra obtained from the data (solid line) for d) e^+e^-, e) $\mu^+\mu^-$, and f) $e^\pm\mu^\mp$; the dashed lines show the background predicted by Monte Carlo.